

Maximizing the ExoEarth Candidate Yield for a Future Direct Imaging Mission

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GSFC NPP Fellow

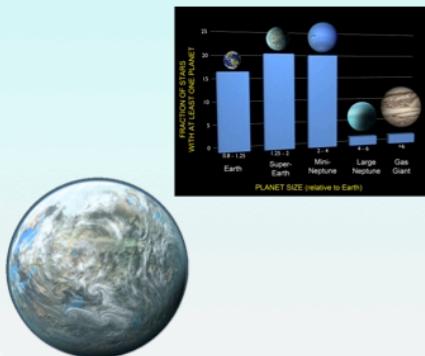
christopher.c.stark@nasa.gov

Aki Roberge, Avi Mandell

Inputs to the ATLAST DRM

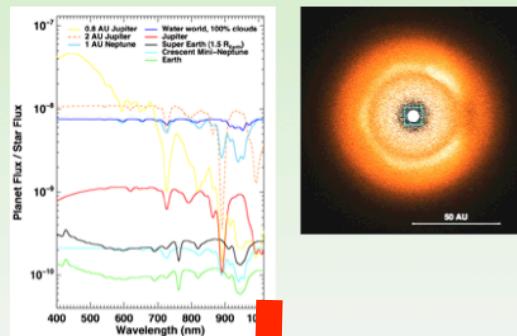
Astrophysical Constraints

- η_{Earth}
- η_{exozodi}
- Planet sizes
- Albedos
- Phase functions



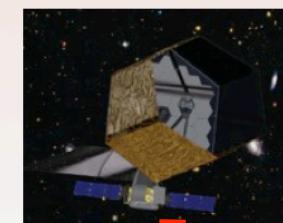
Observational Requirements

- Central wavelength
- Total bandpass
- Spectral resolution
- Signal-to-Noise
- Observing strategy



Technical Requirements

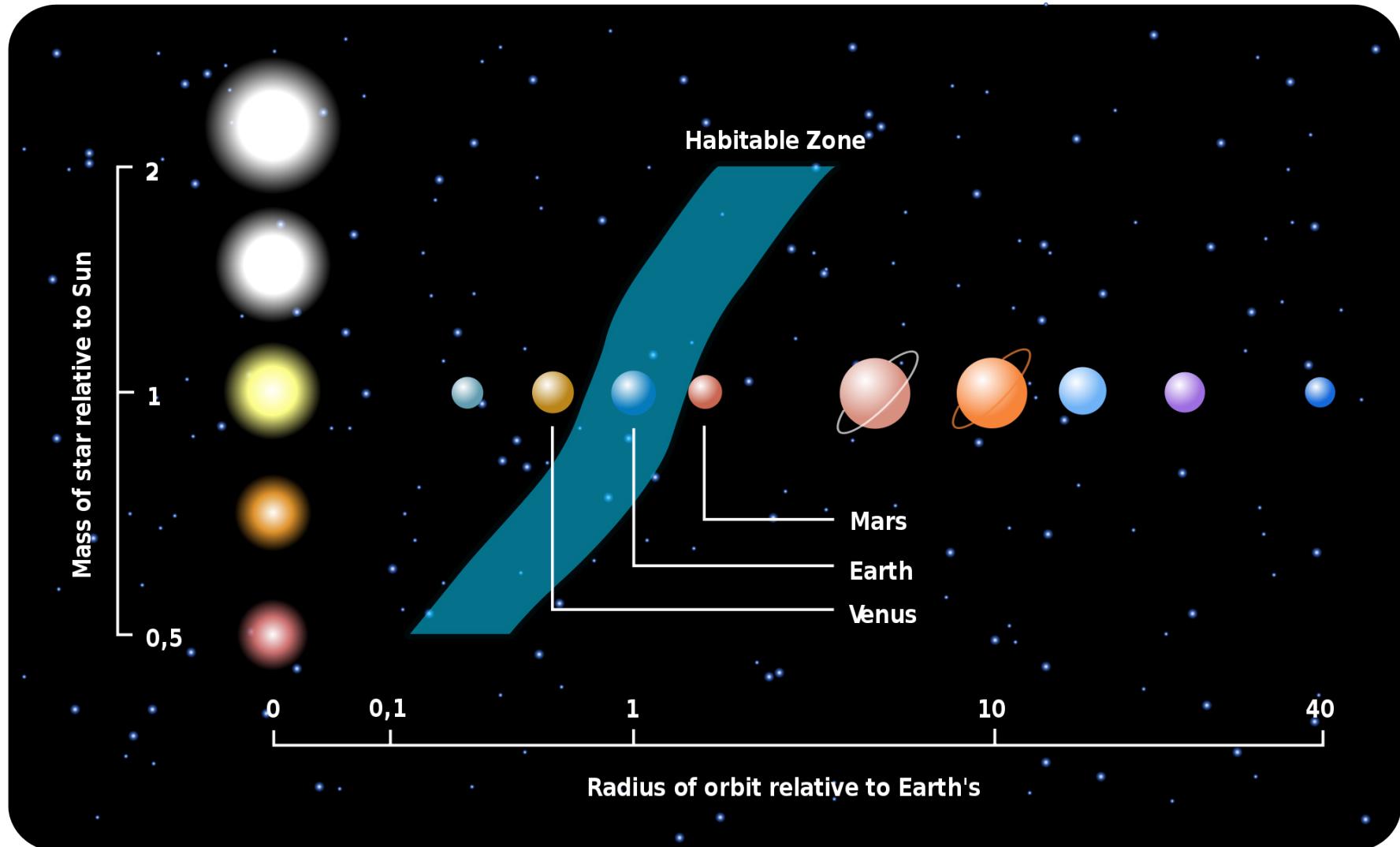
- Telescope diameter
- Contrast
- Contrast floor
- Inner working angle
- Outer working angle
- Total throughput
- Overheads



DRM

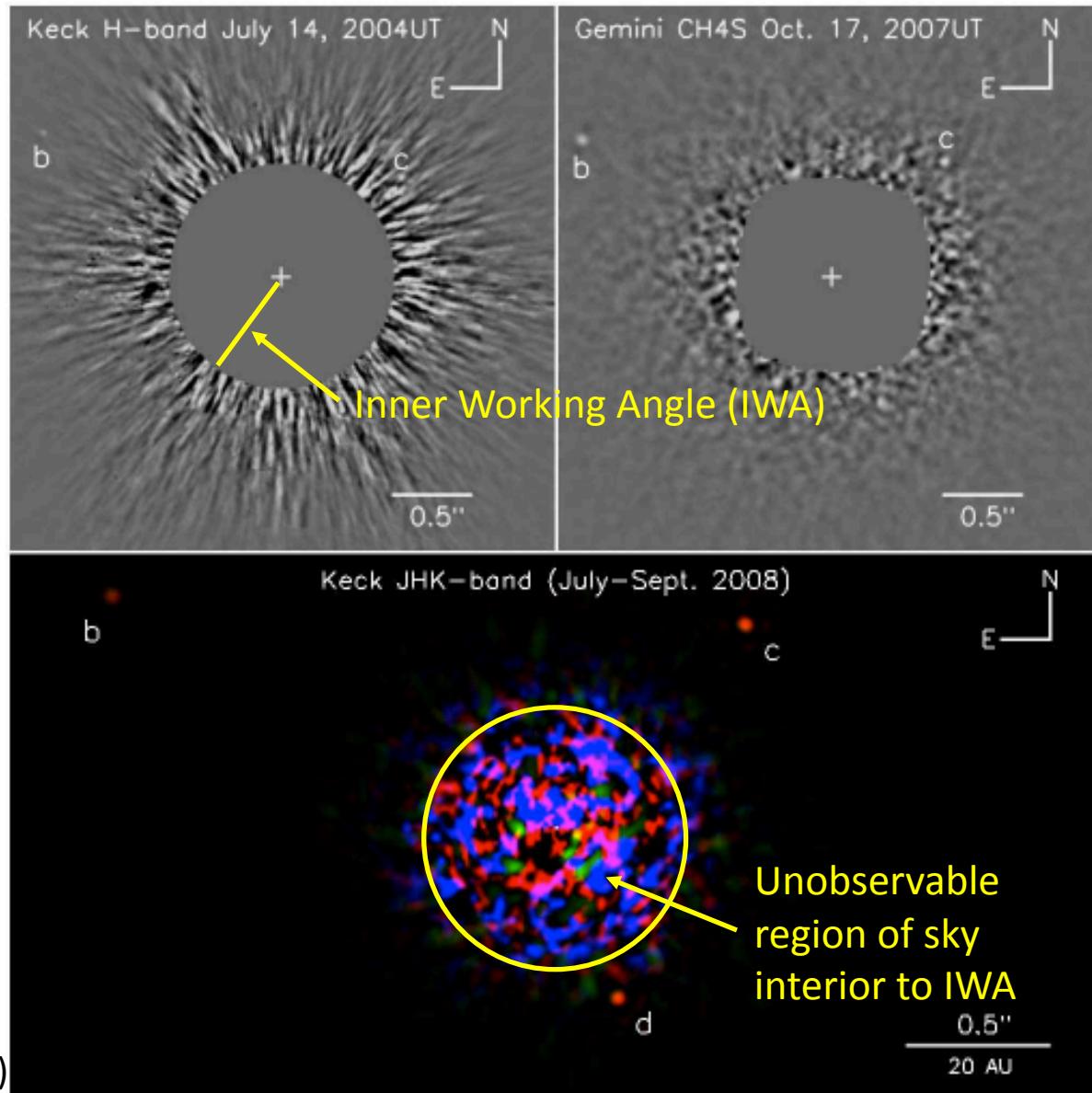
ExoEarth Candidate Yield

Goal: Image Earth-like Planets in the Habitable Zone

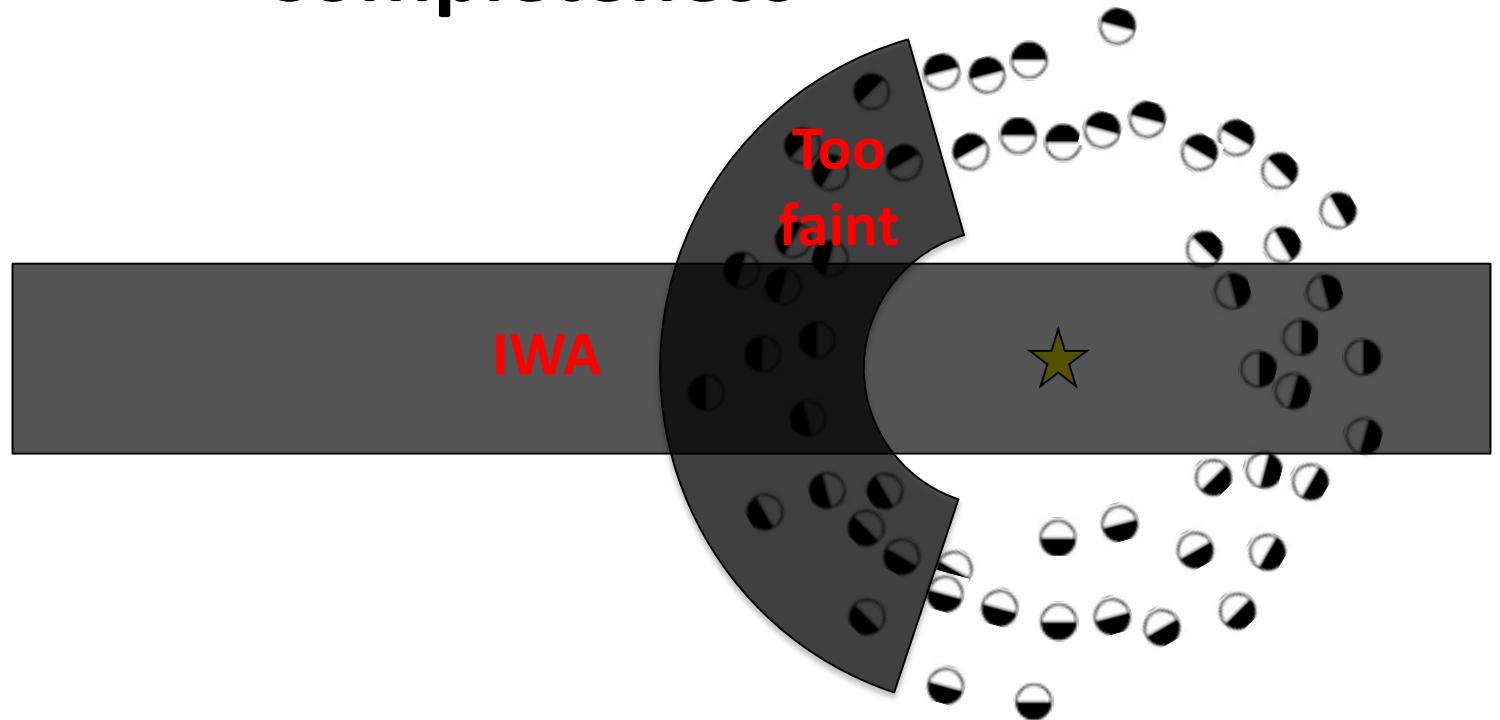
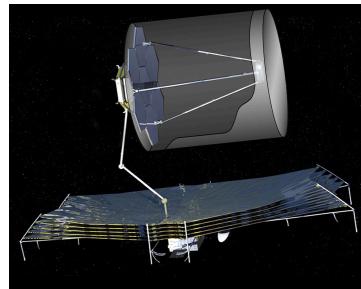


We assume the ExoEarth definition described in Brown (2005) ³

Method: High-Contrast Imaging



How To Calculate Planet Yield: Completeness



“Completeness” = the chance of observing a given planet around a given star if that planet exists

Calculated via a Monte Carlo simulation with synthetic planets

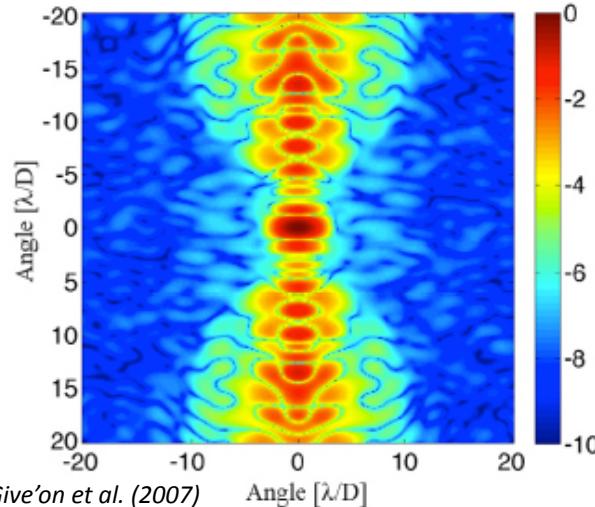
Depends on distance to star, planet’s orbit, radius, albedo, and phase function, and the exposure time for the required SNR

How To Calculate Planet Yield: Exposure Time

$$\tau = (\text{Planet SNR})^2 \times \frac{(\text{Planet count rate}) + 2 \times (\text{Background count rate})}{(\text{Planet count rate})^2}$$

Background count rate =

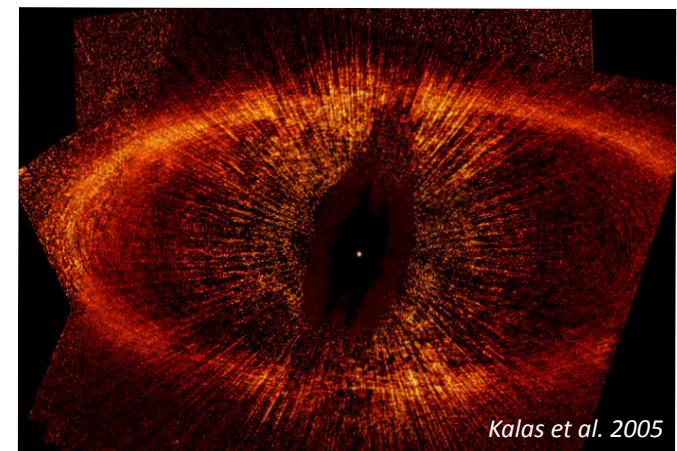
Leaked starlight



+ Zodiacal light



+ Exozodiacal light



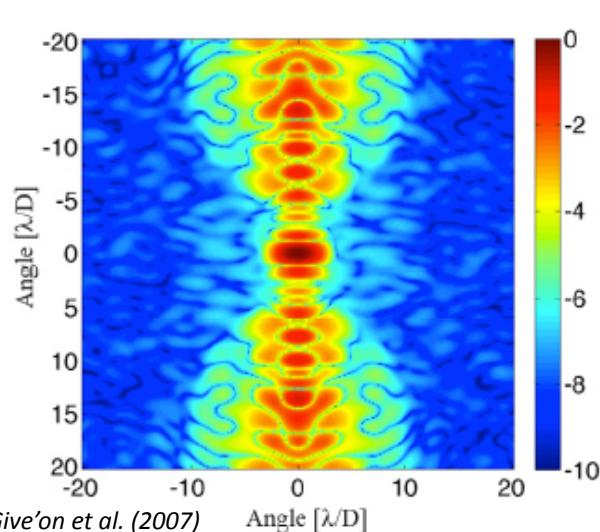
How To Calculate Planet Yield: Exposure Time

$$\tau = \frac{(\text{Planet SNR})^2 \times (\text{Planet count rate}) + 2 \times (\text{Background count rate})}{(\text{Planet count rate})^2}$$

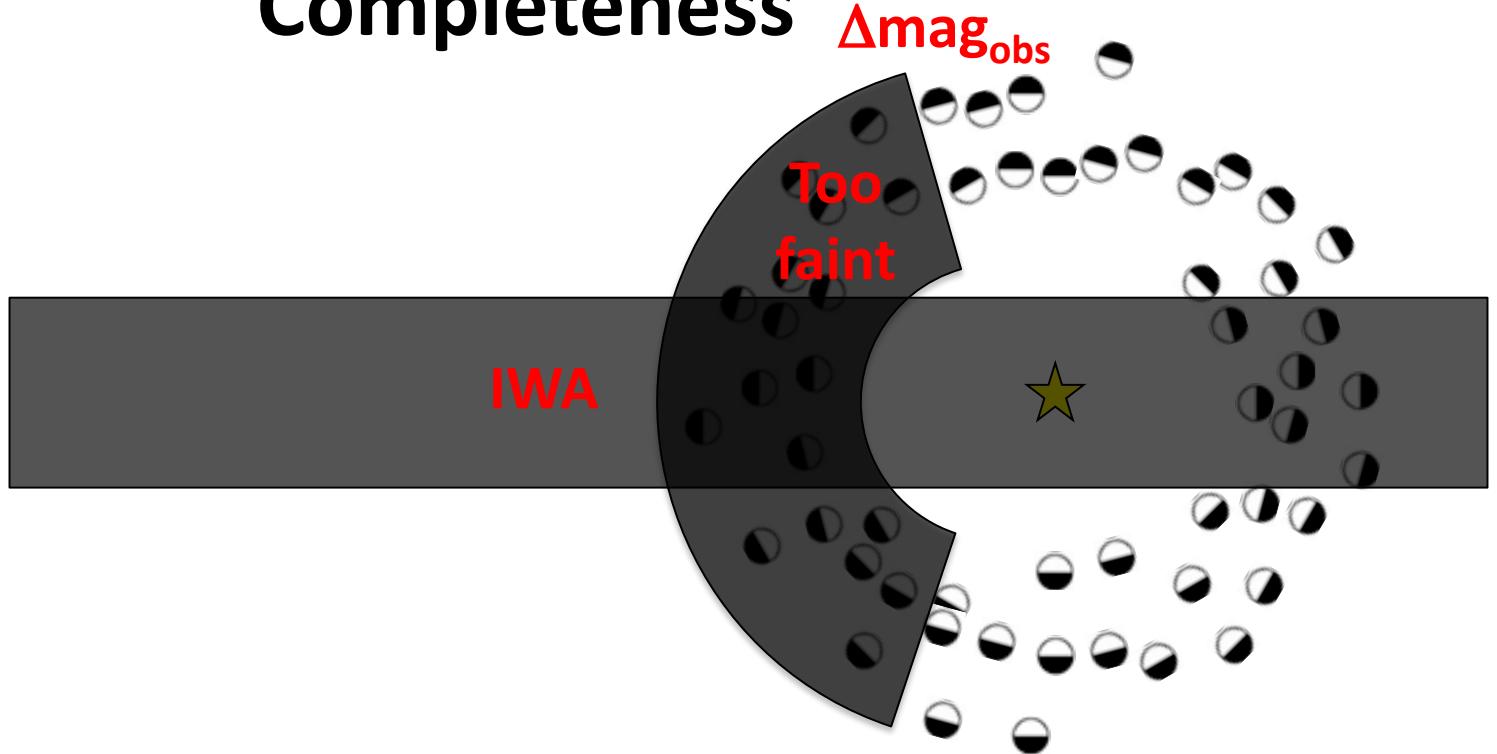
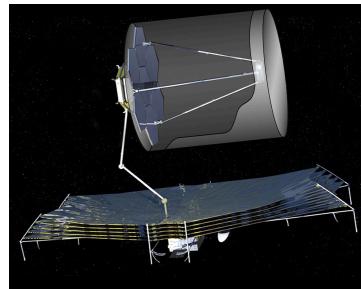
$\Delta\text{mag}_{\text{obs}}$

Background count rate =

Leaked starlight + Zodiacal light + Exozodiacal light



How To Calculate Planet Yield: Completeness



“Completeness” = the chance of observing a given planet around a given star if that planet exists

Calculated via a Monte Carlo simulation with synthetic planets

Depends on distance to star, planet’s orbit, radius, albedo, and phase function, and the exposure time for the required SNR

How To Calculate Planet Yield: Maximizing Yield

Combines output from completeness calculator and exposure time calculator to prioritize target list.

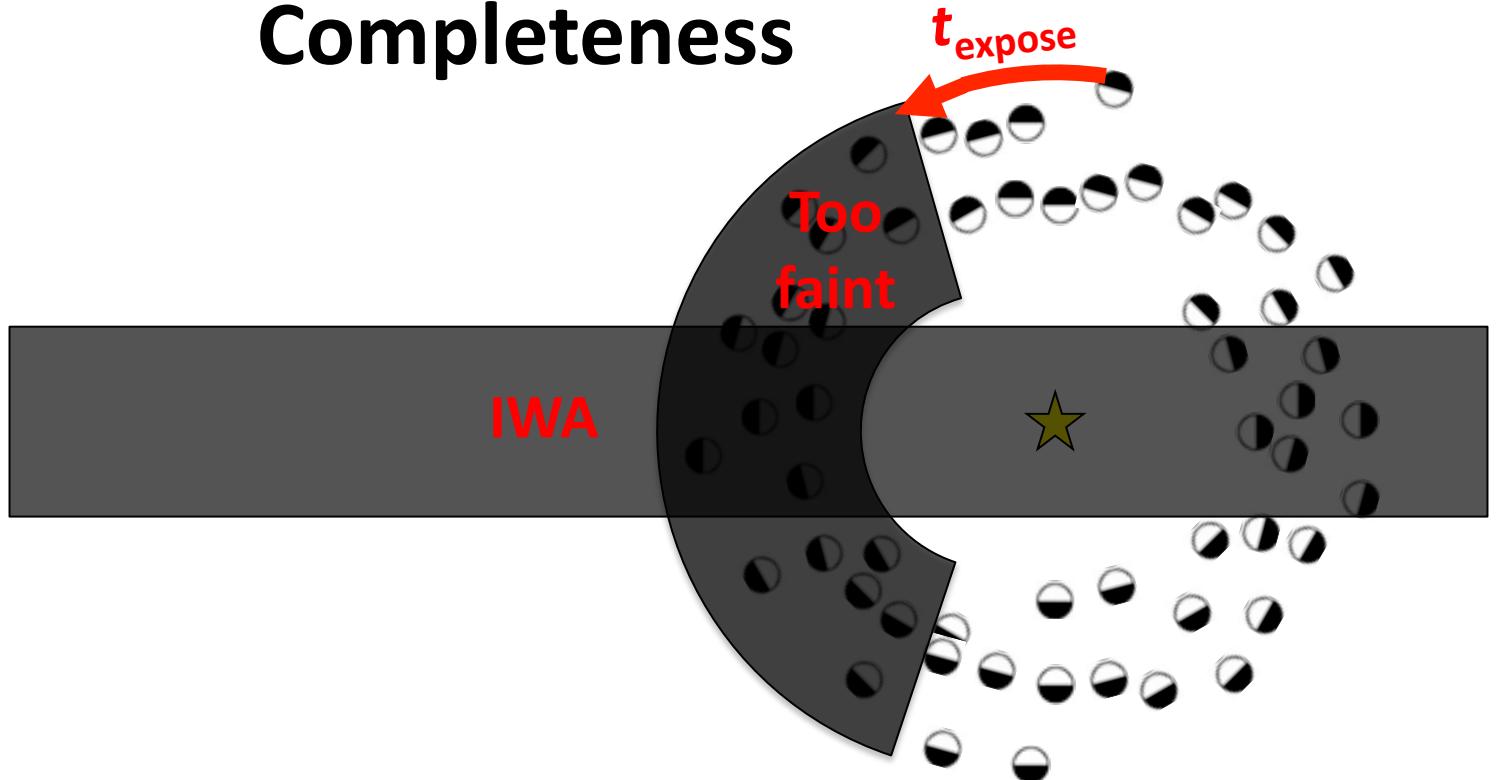
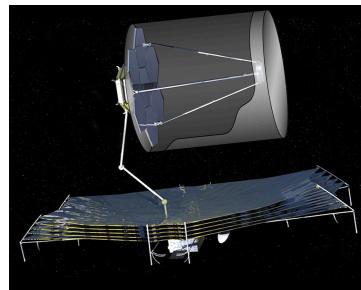
For each star in target list...

- Assume a $\Delta\text{mag}_{\text{obs}}$
 - Completeness = $C(\Delta\text{mag}_{\text{obs}}, \text{IWA}, \text{OWA})$
 - Exposure time = $\tau(\Delta\text{mag}_{\text{obs}})$
- Calculate a benefit to cost ratio = completeness / exposure time

For target list ensemble...

- Prioritize target list by benefit to cost ratio
- Sum exposure+overhead times of high priority targets until total mission lifetime is exceeded
- $N_{\text{stars}} = \# \text{ of stars observed within the given mission lifetime}$
- $N_{\text{exoEarths}} = \text{Total completeness obtained over mission} \times \eta_{\text{Earth}}$

How To Calculate Planet Yield: Completeness

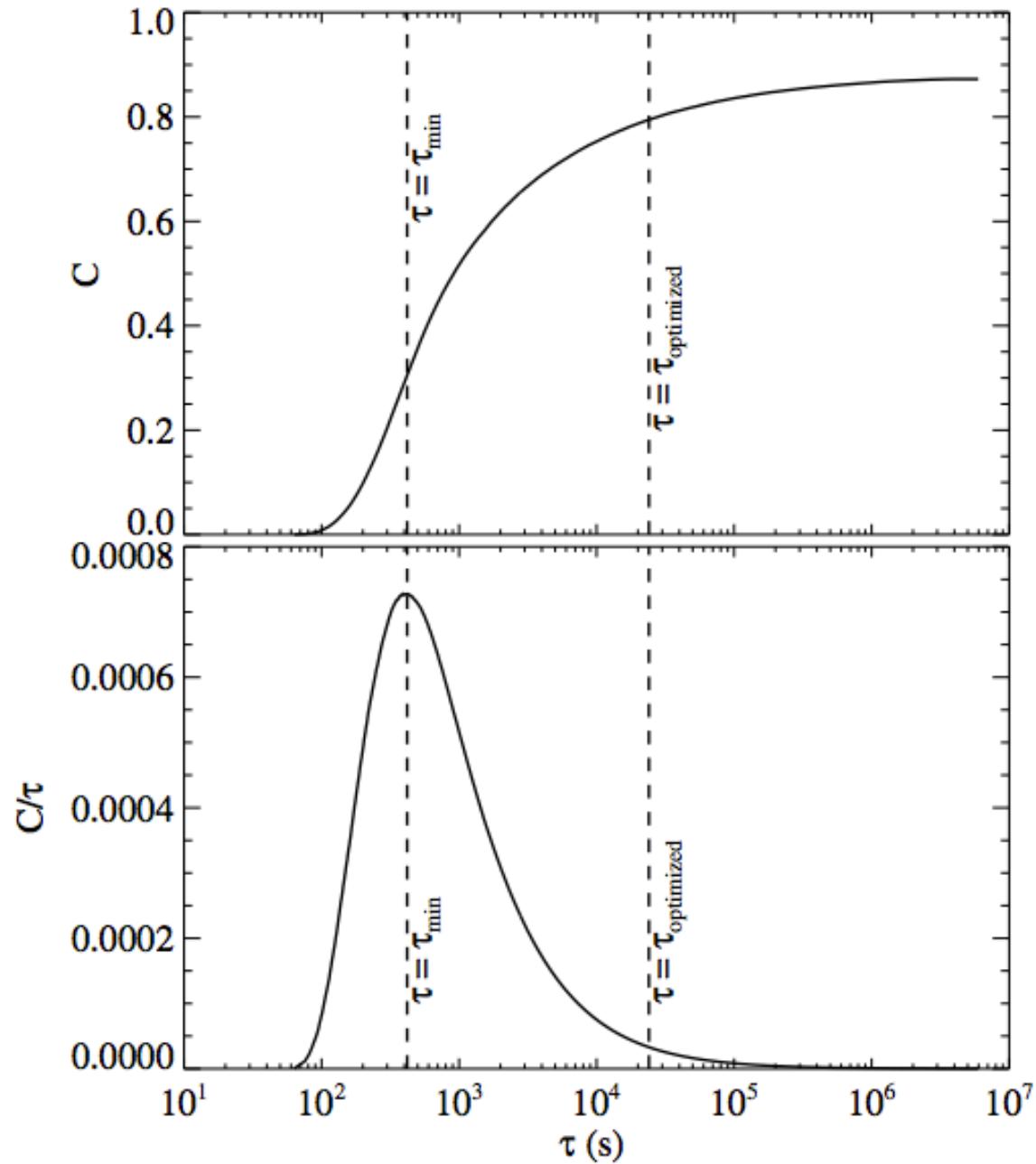


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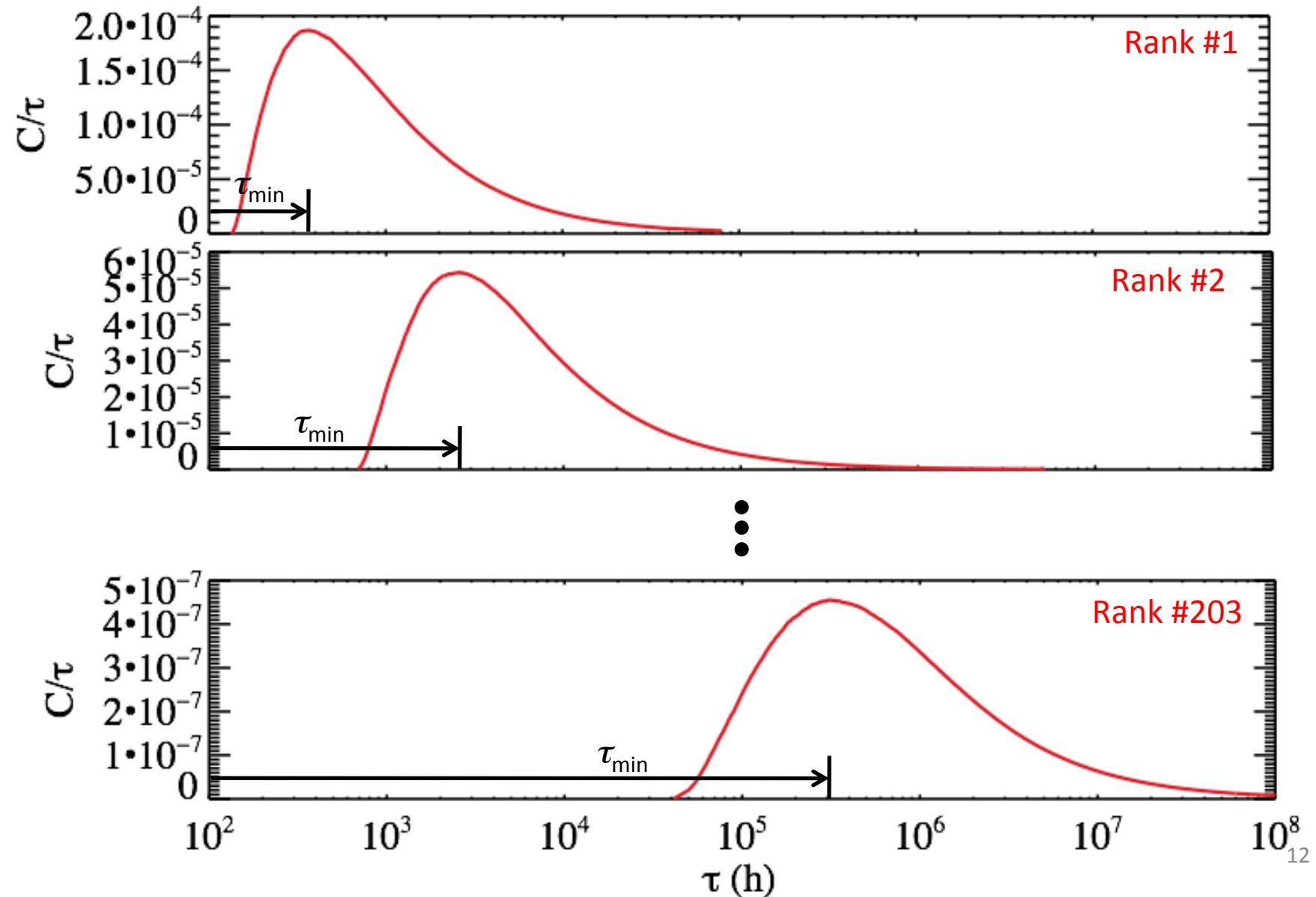
Depends on distance to star, planet’s orbit, radius, albedo, and phase function, and the exposure time for the required SNR

Maximizing ExoEarth Yield with Completeness Curves



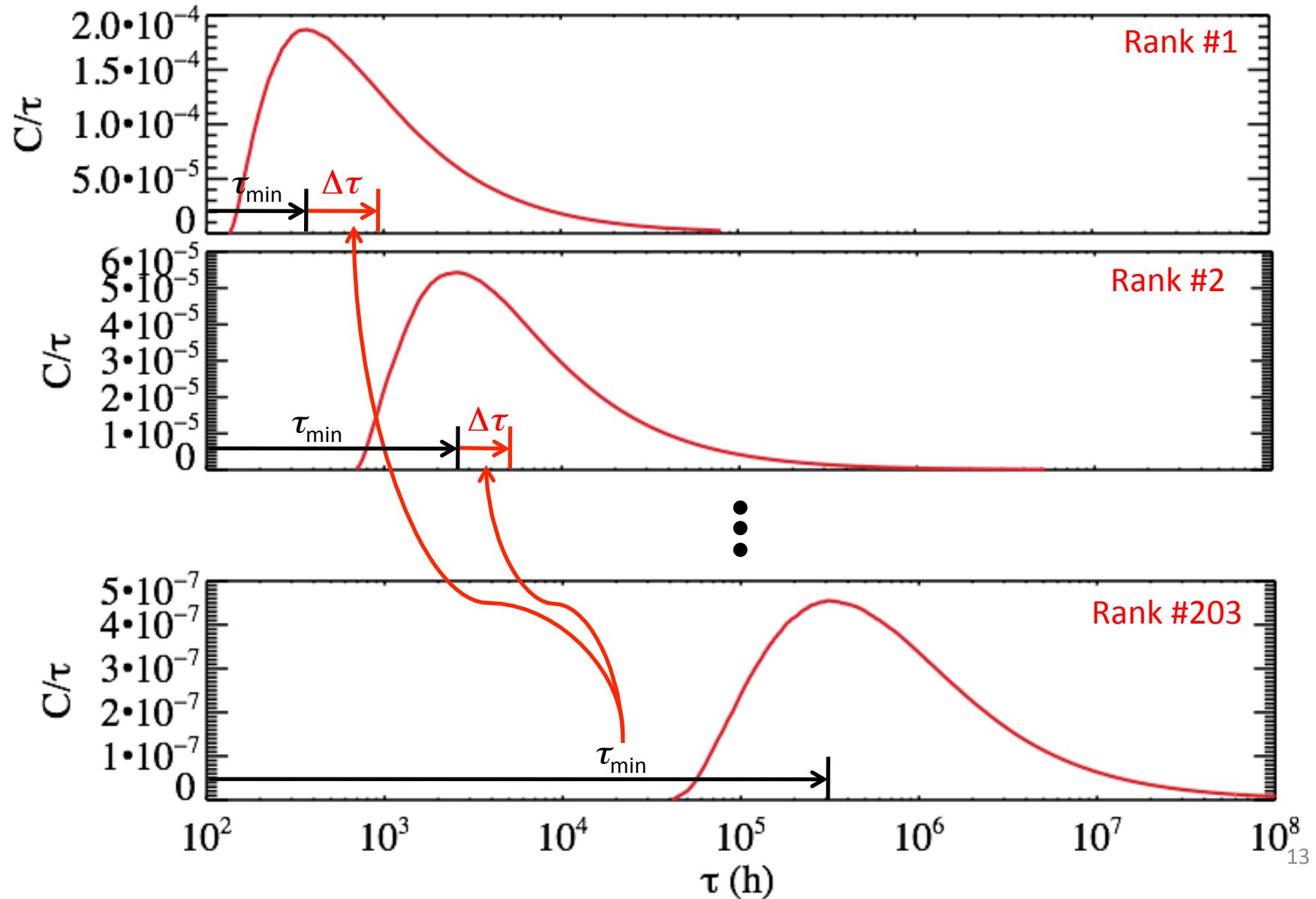
Altruistic Yield Optimization (AYO)

Observe all targets for τ_{\min} & select highest priority targets with $\sum \tau_{\min} < t_{\text{mission}}$

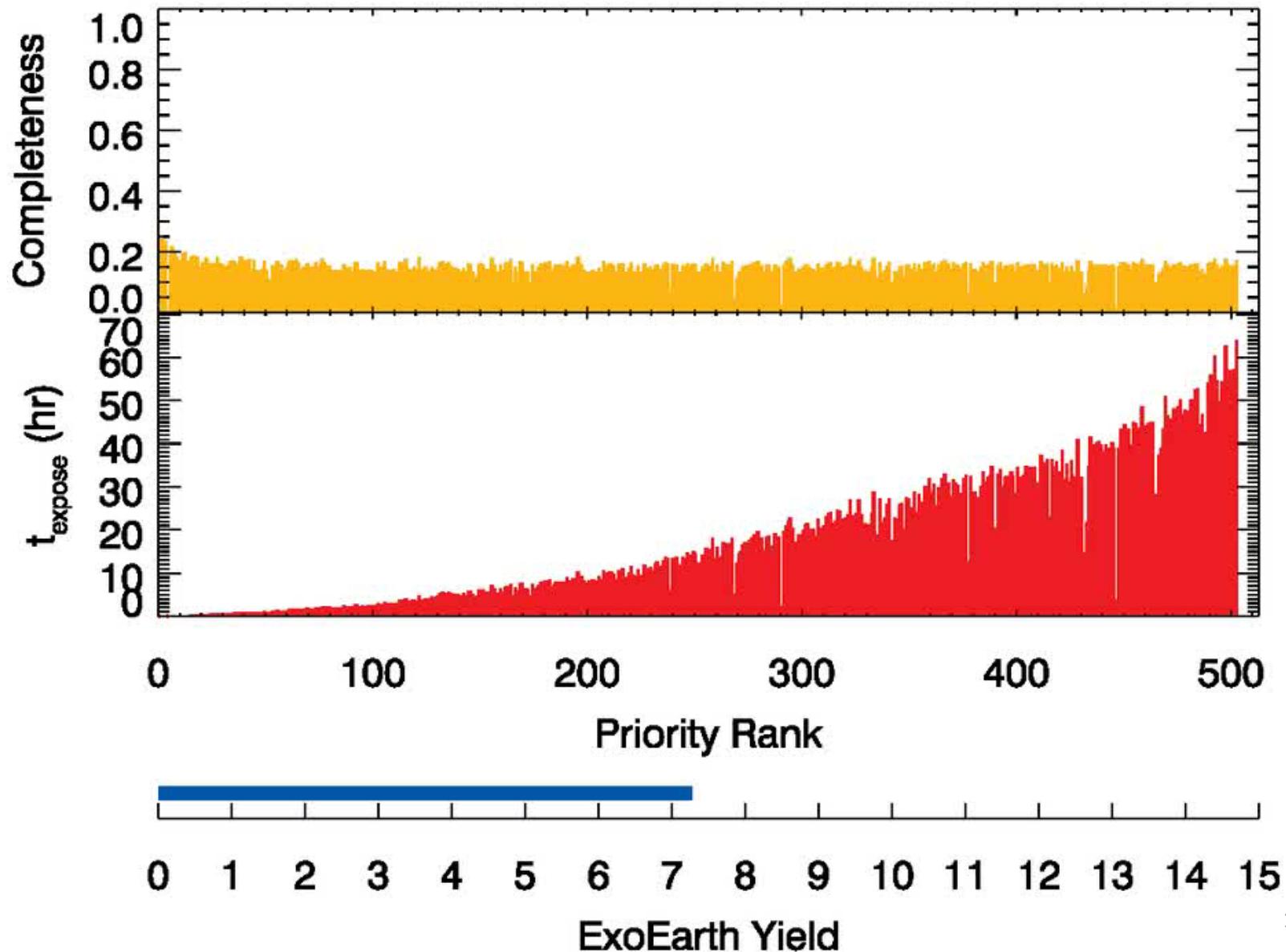


Altruistic Yield Optimization (AYO)

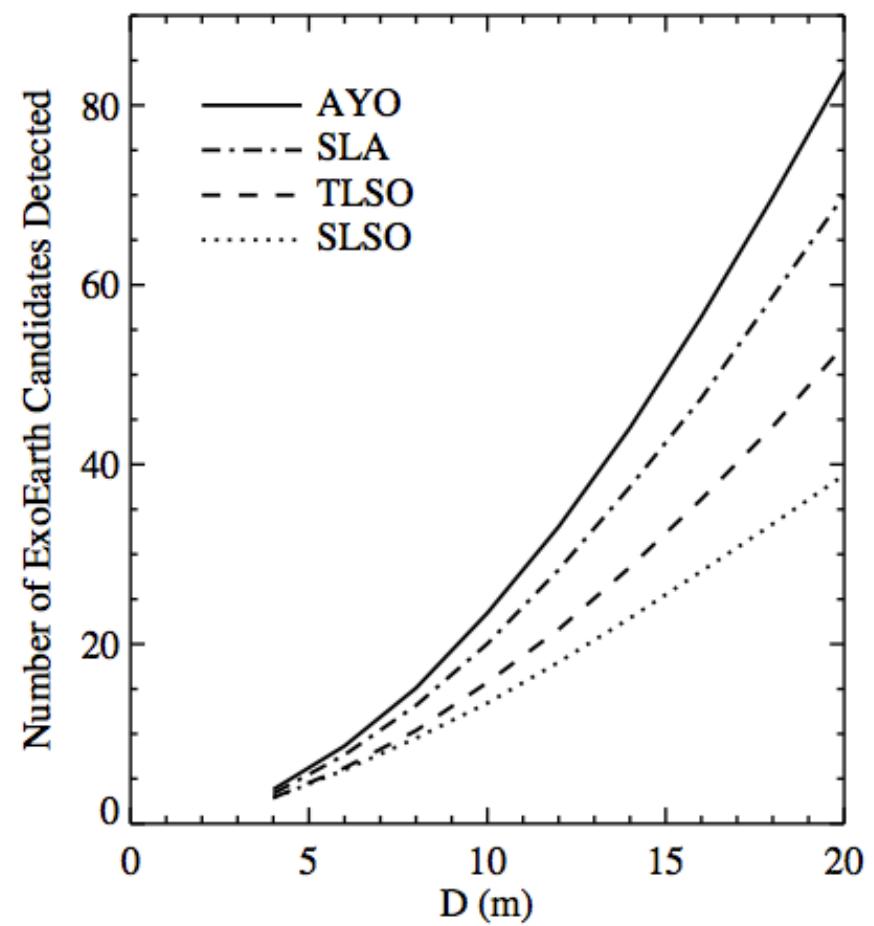
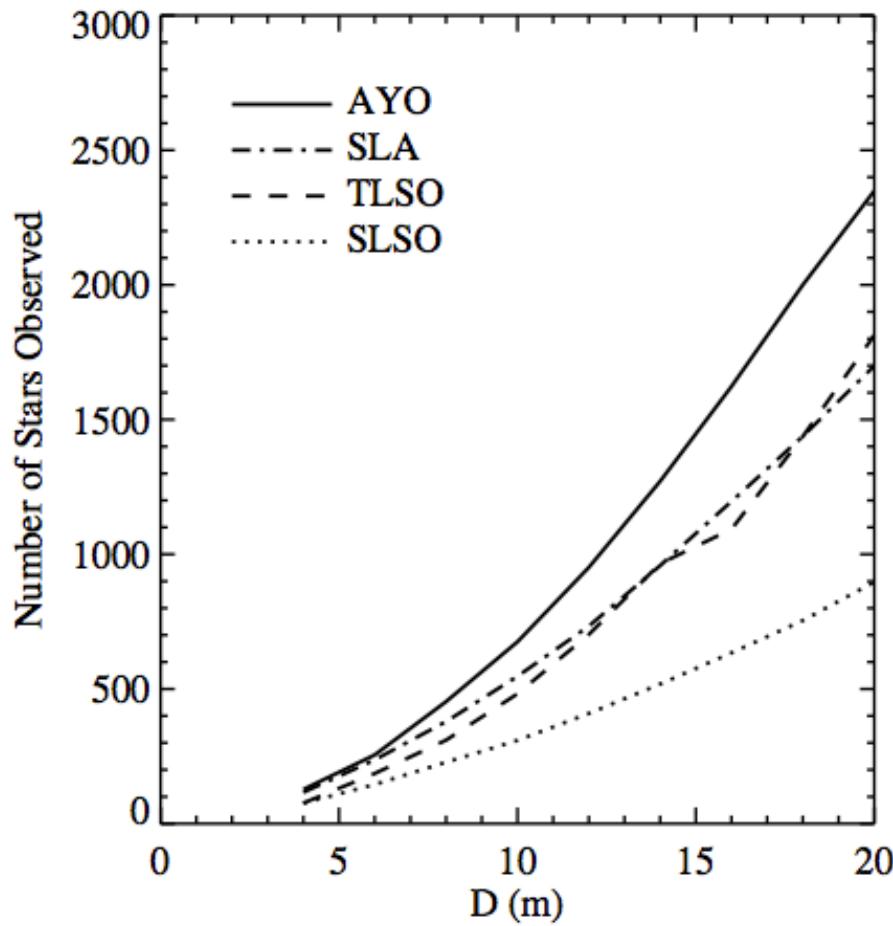
Take τ_{\min} from lowest priority target and divvy up to those with highest $dC/d\tau$



Altruistic Yield Optimization (AYO)



ExoEarth Yield: Method Comparison

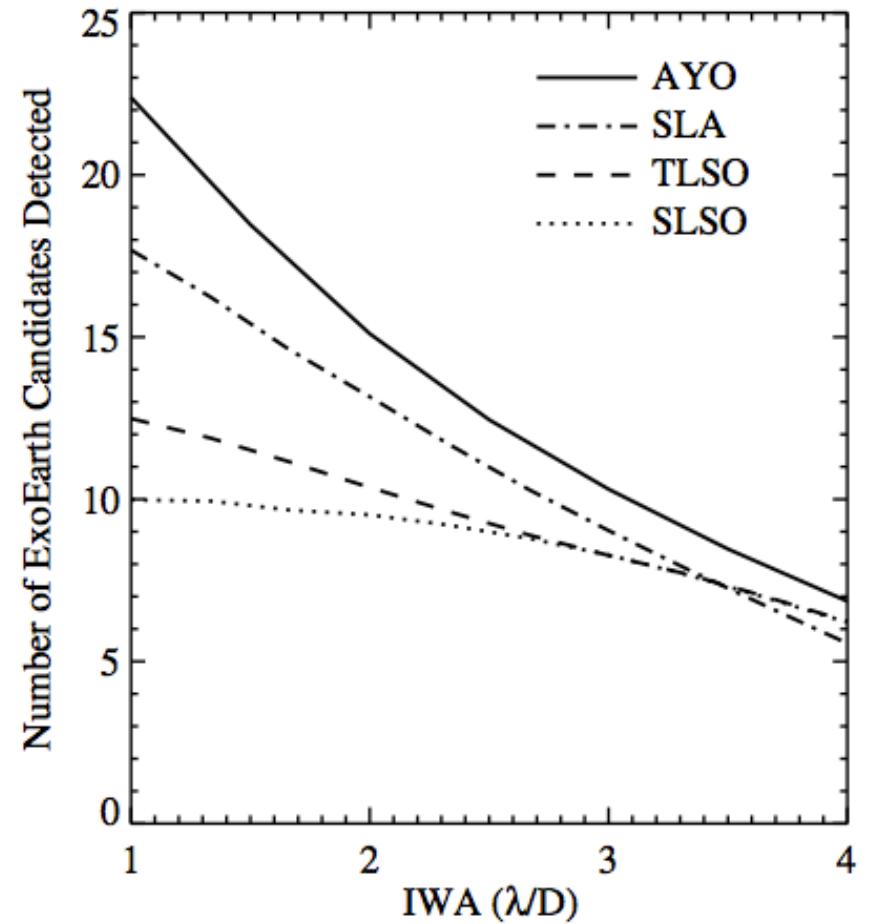
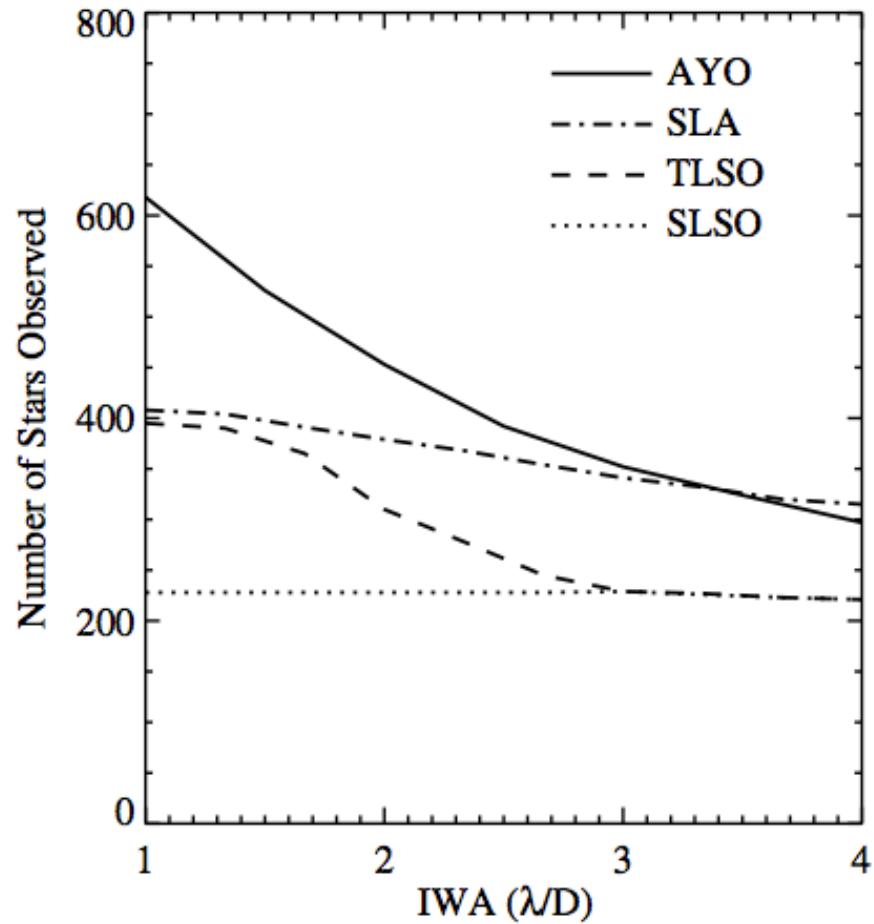


SLSO: e.g. Brown & Soummer (2010)

TLSO: Brown (2005)

SLA: Turnbull et al. (2012)

ExoEarth Yield: Method Comparison

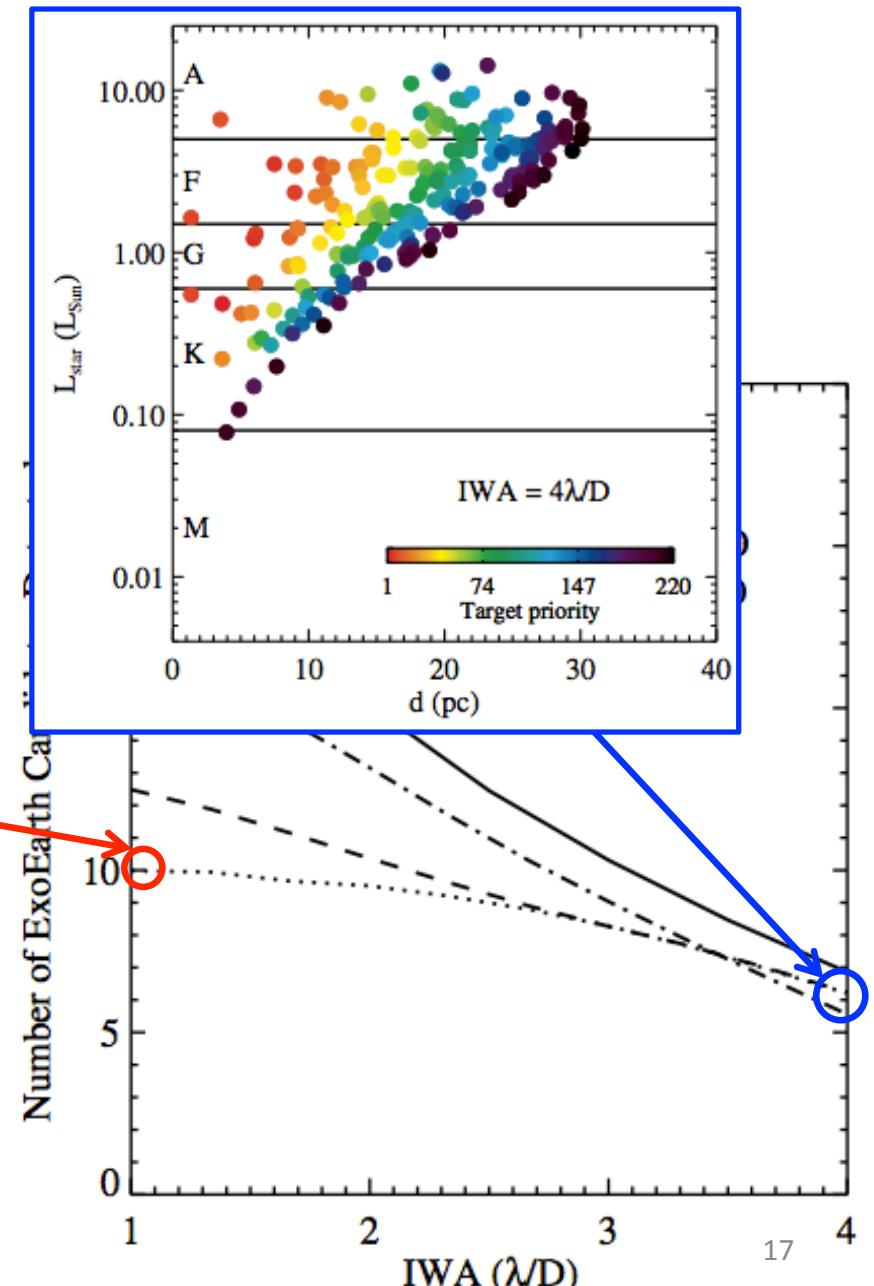
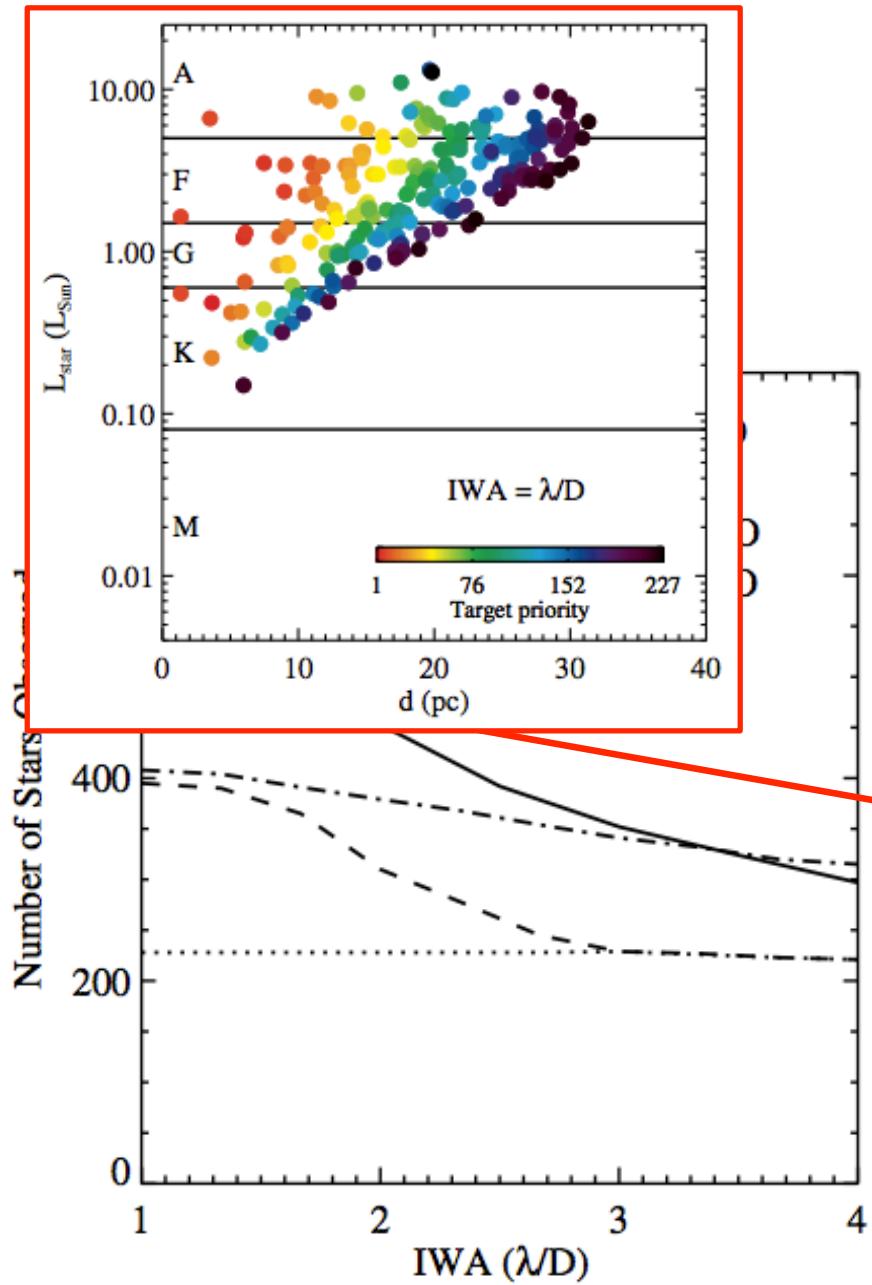


SLSO: e.g. Brown & Sosmer (2010)

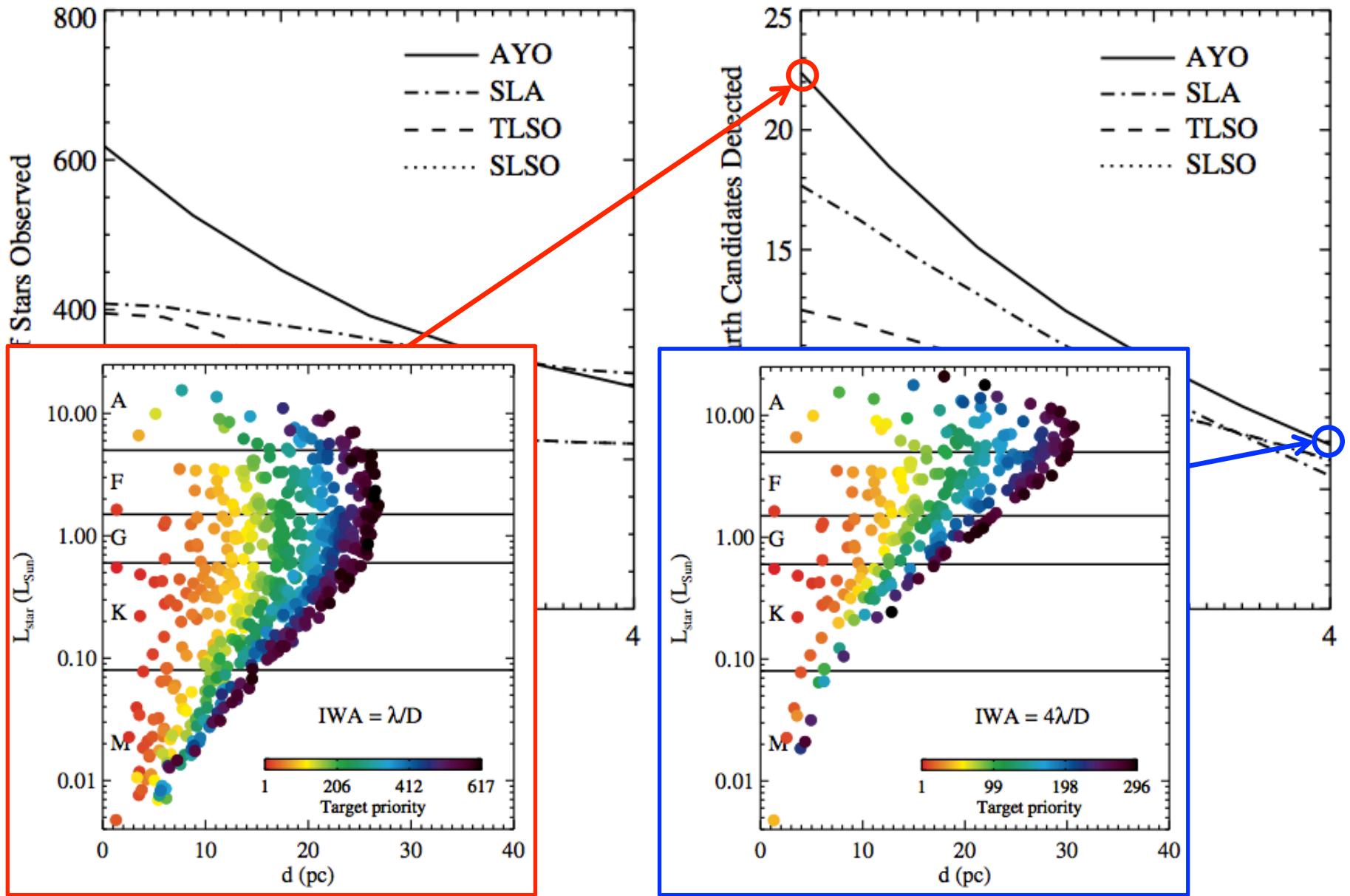
TLSO: Brown (2005)

SLA: Turnbull et al. (2012)

ExoEarth Yield: Method Comparison



ExoEarth Yield: Method Comparison



ExoEarth Candidate Yield: Exploring Parameter Space

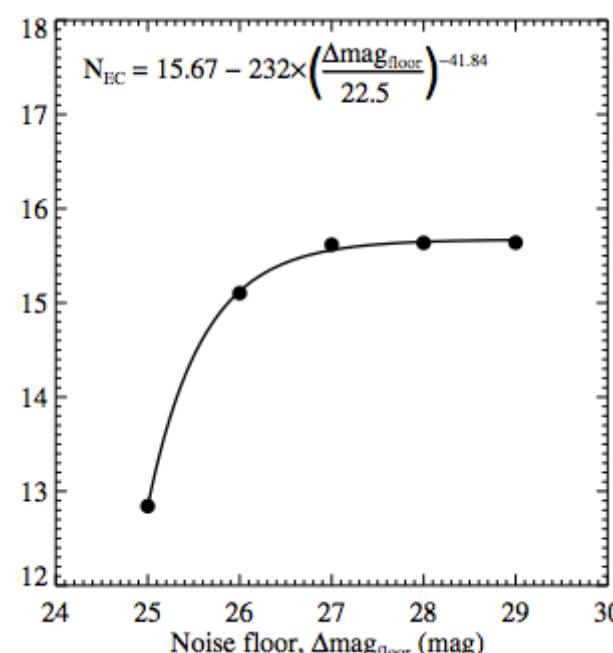
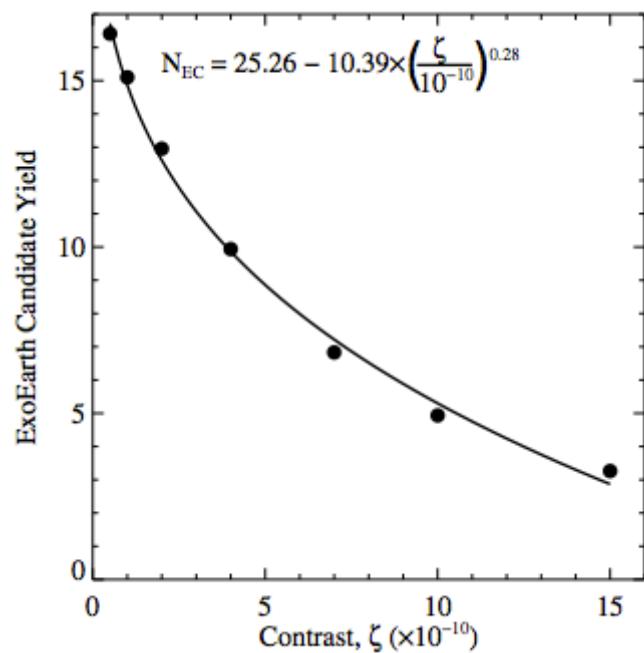
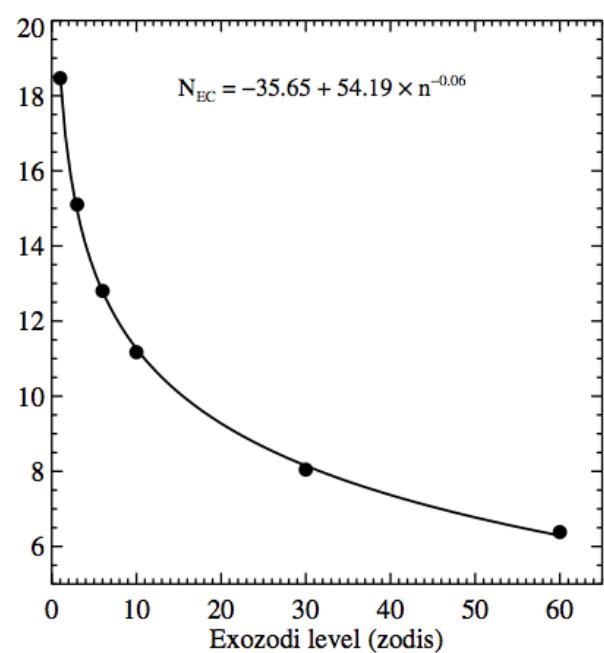
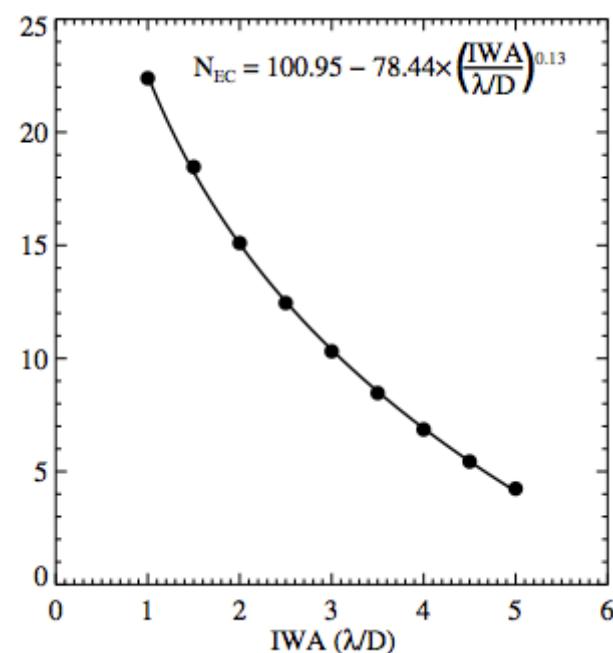
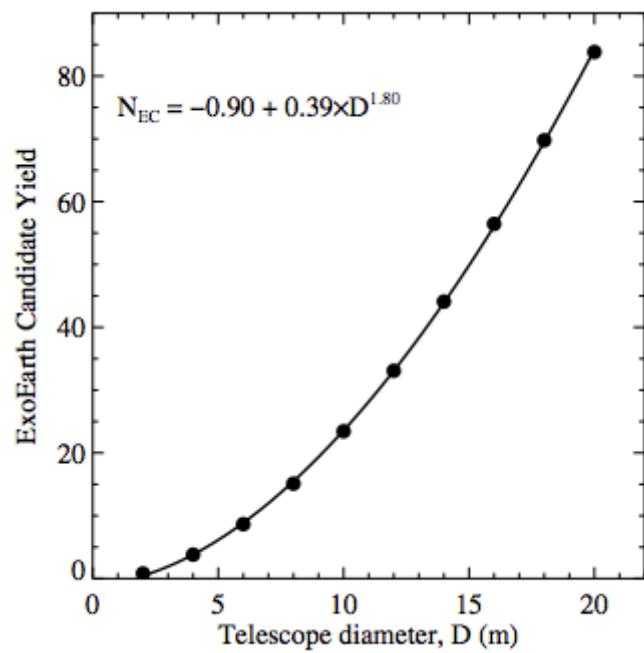
- 10 values of D: 2-20 m
- 9 values of IWA: 1-5 λ/D
- 7 values of contrast, ζ : 5×10^{-11} to 1.5×10^{-9}
- 5 values of $\Delta\text{mag}_{\text{floor}}$: [0,1,2,3,4] - $2.5 \times \log(\zeta)$
- 6 values of exozodi level, n: [1,3,6,10,30,60] zodis

Total of ~19,000 models run

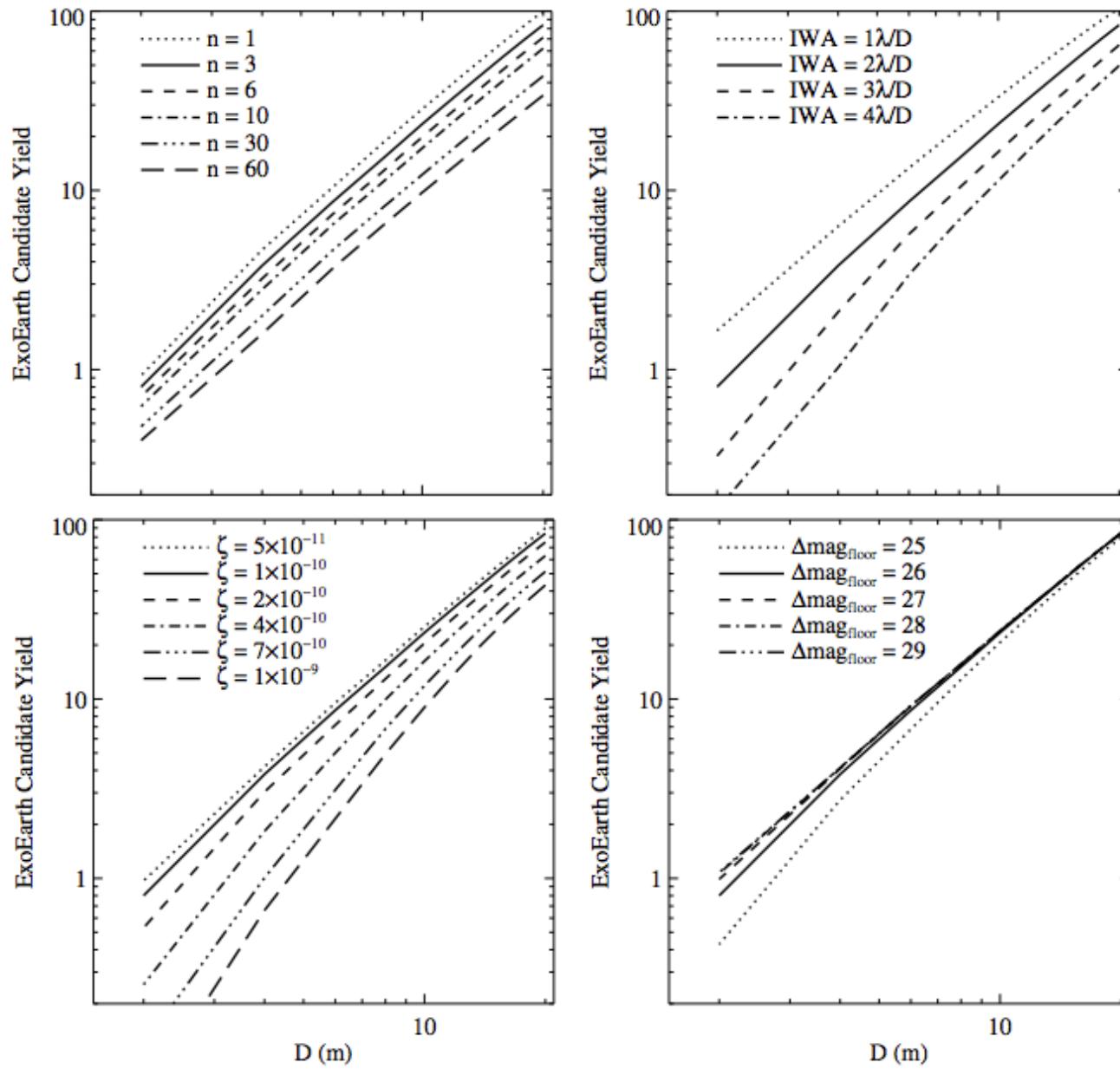
ExoEarth Candidate Yield

The Baseline Mission:

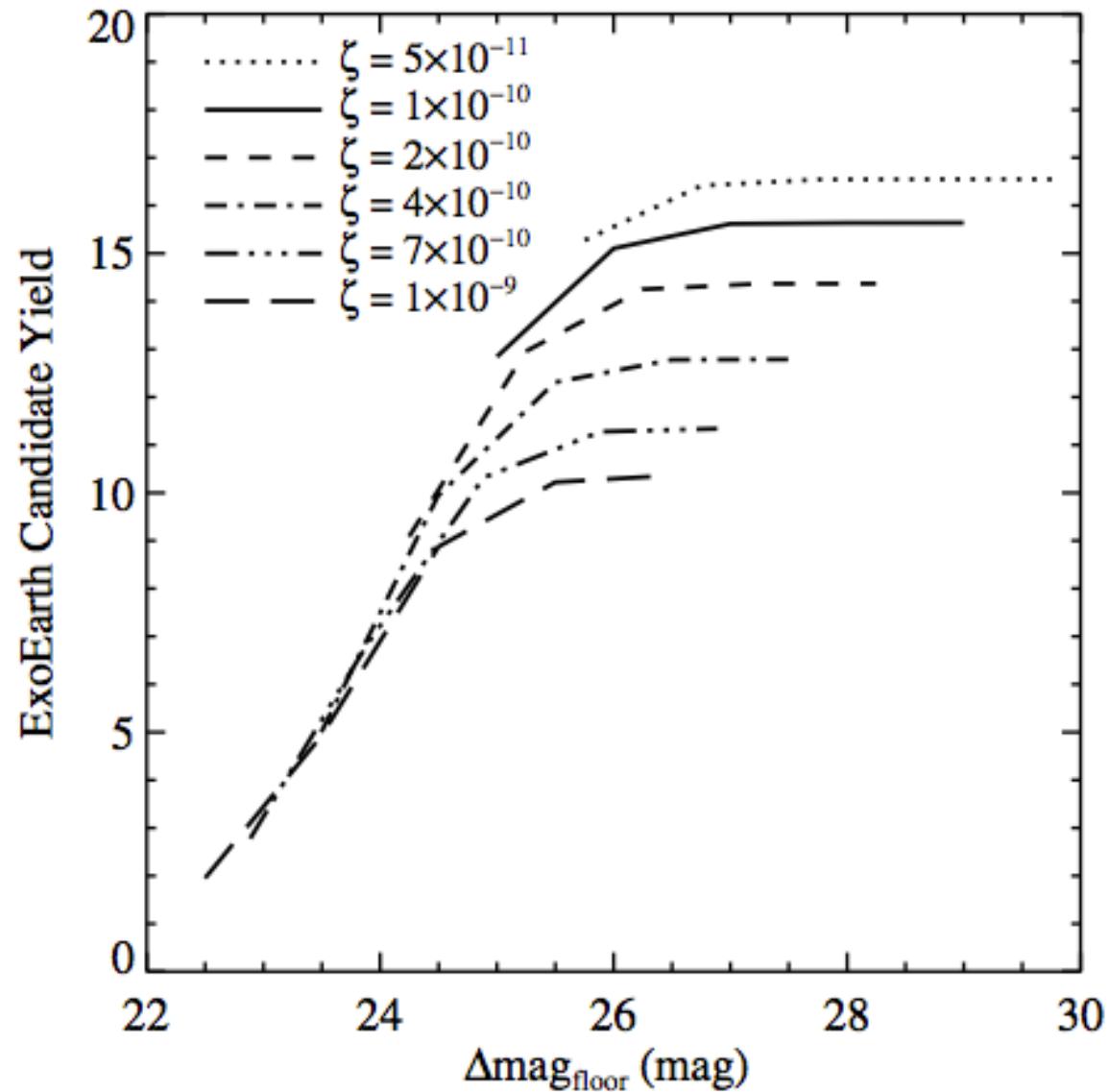
- $D = 8 \text{ m}$
- Contrast, $\zeta = 10^{-10}$
- $\Delta\text{mag}_{\text{floor}} = 26$ (i.e. $\zeta_{\text{floor}} = 4 \times 10^{-11}$)
- IWA = $2\lambda/D$, OWA = $15\lambda/D$
- $n_{\text{exozodis}} = 3$
- throughput = 0.2
- $\lambda = 0.55 \mu\text{m}$, $\Delta\lambda = 0.11 \mu\text{m}$
- $\eta_{\text{Earth}} = 0.1$
- 1 year of observation time
- No time allocated for spectra
- No revisits
- No overheads



Yield vs. D

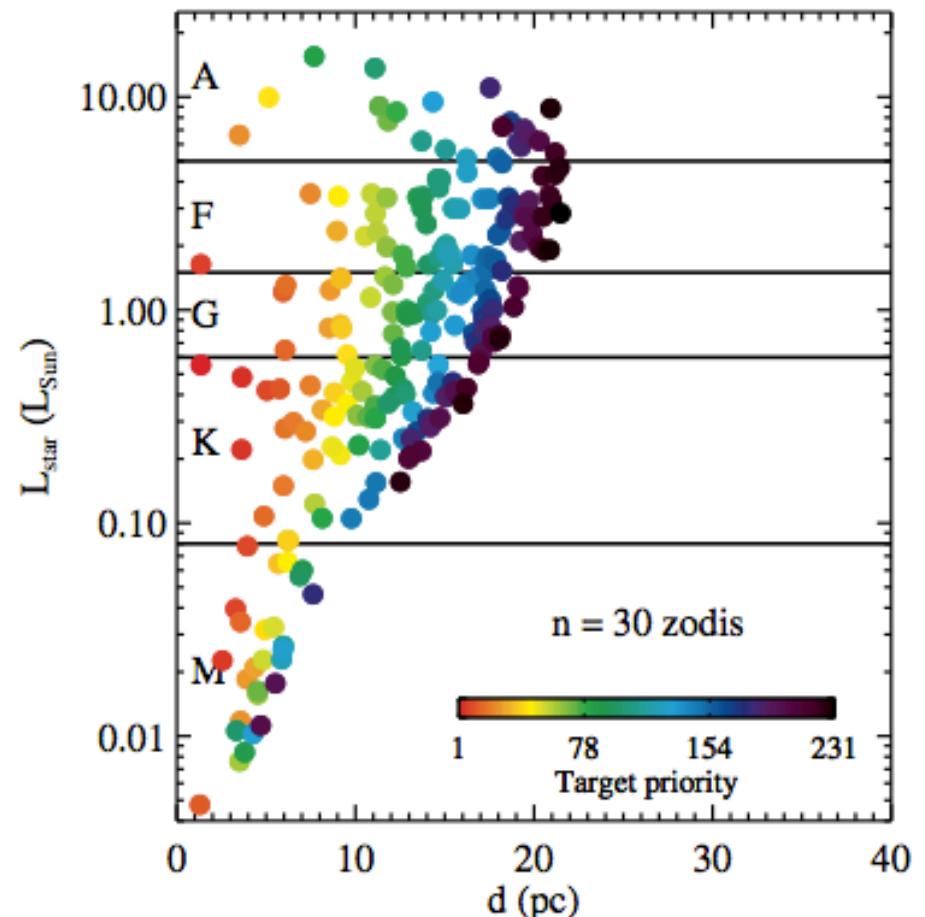
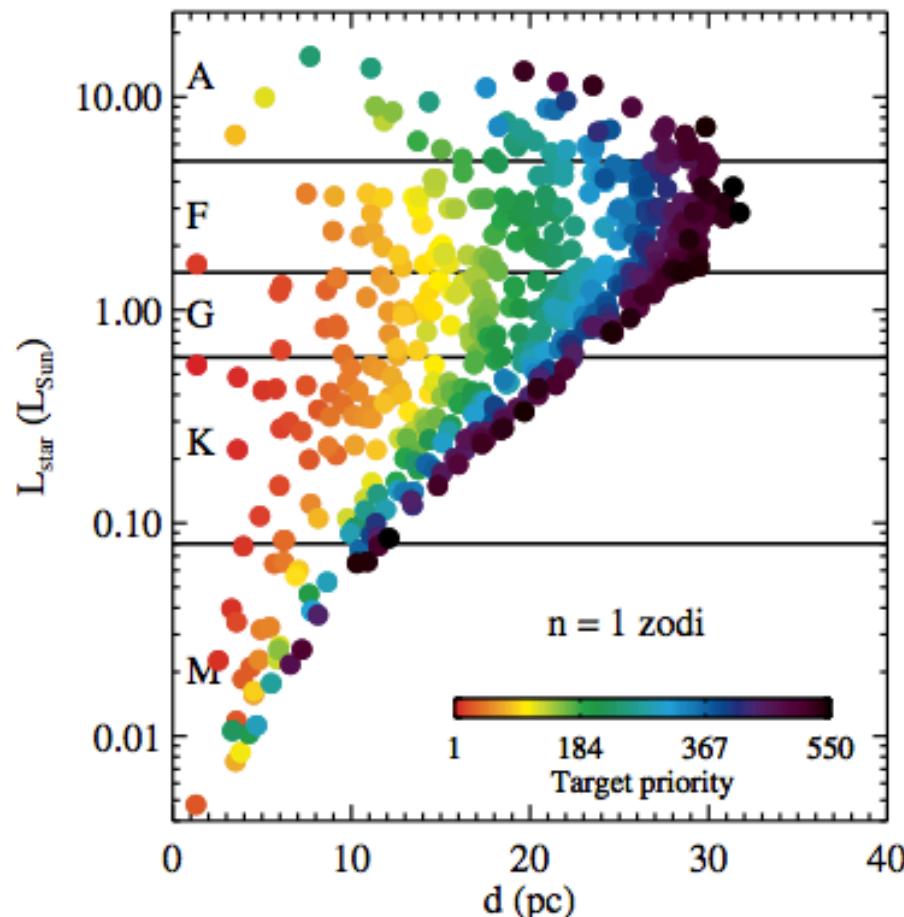


Constraining the Systematic Noise Floor



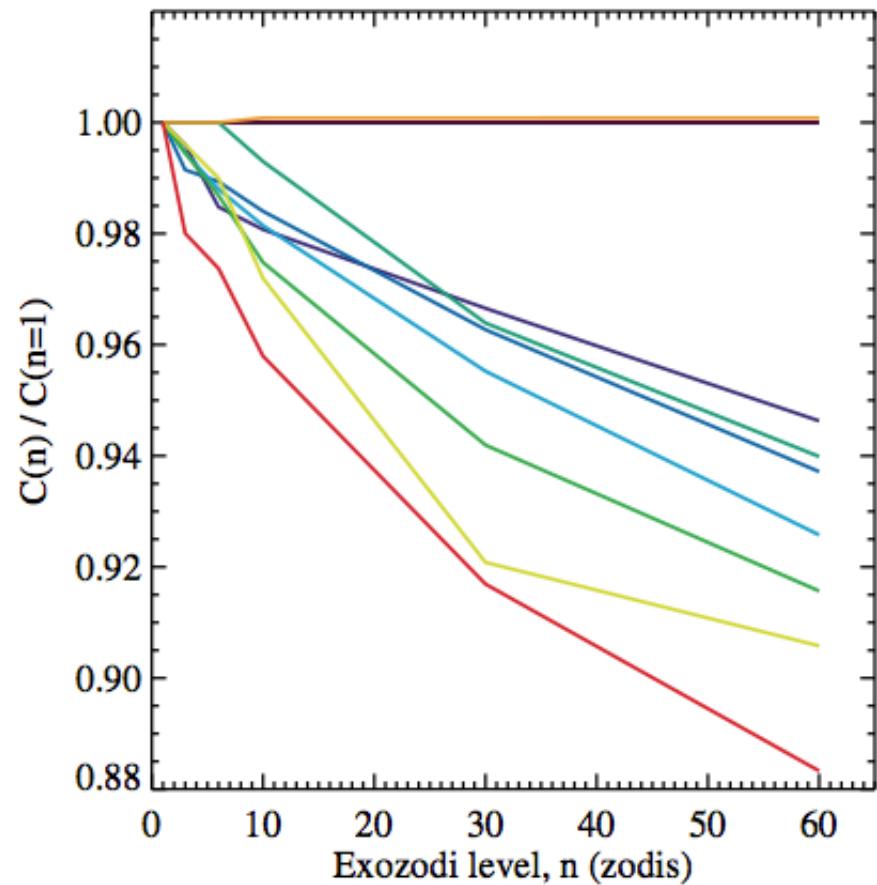
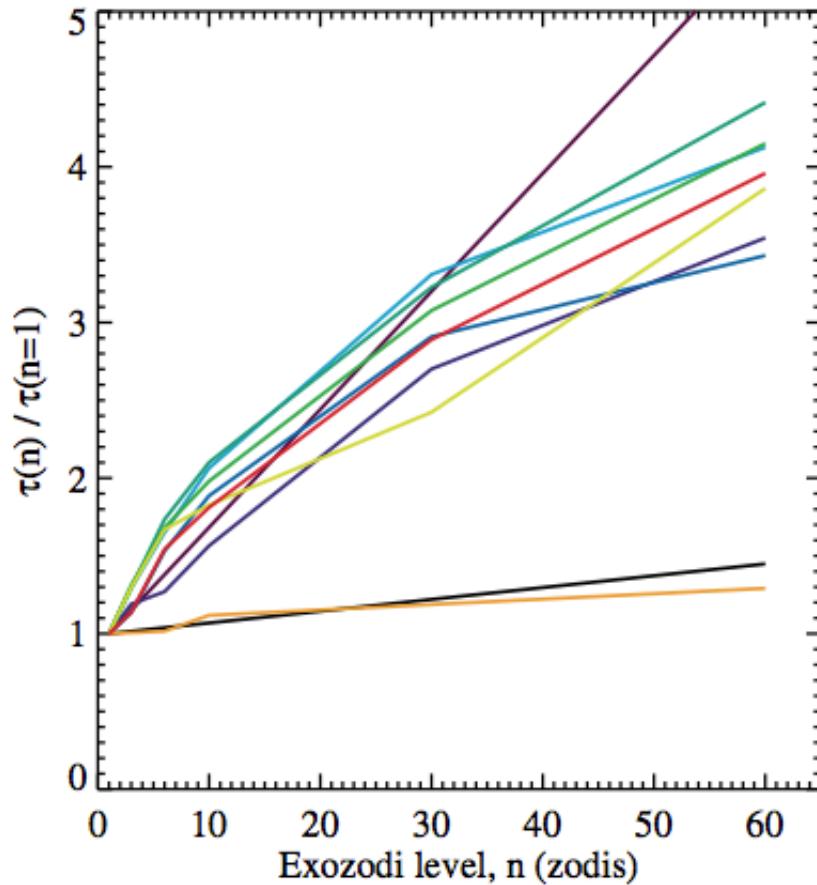
$\Delta\text{mag}_{\text{floor}} > 26$ provides little additional yield

Why is the Exozodi Dependence so Weak?



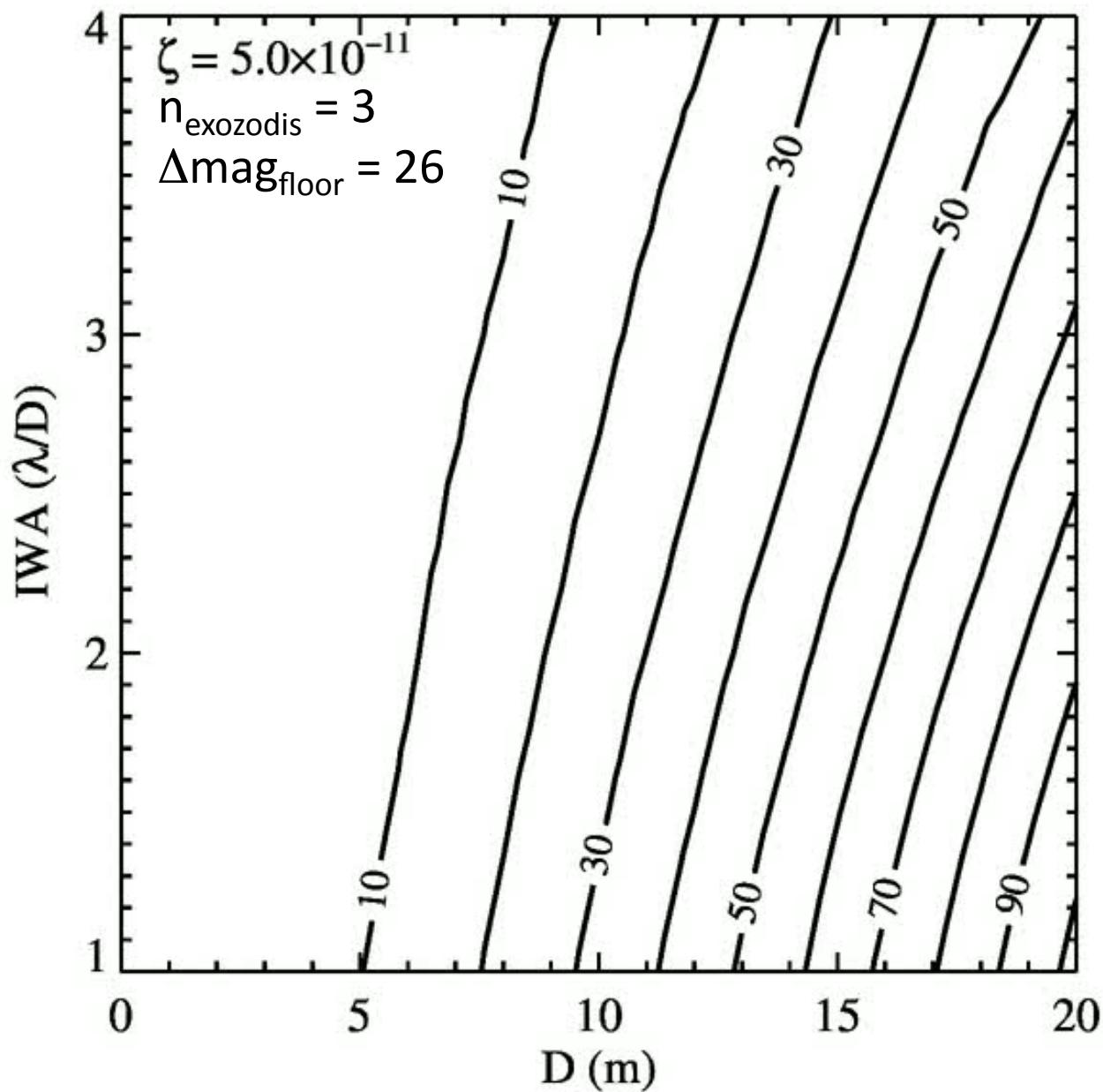
1. Increasing exozodi naturally removes the *worst* targets

Why is the Exozodi Dependence so Weak?



2. AYO sacrifices exposure time and completeness to observe more stars, which maximizes yield

ExoEarth Yield Contours



How Many ExoEarth Candidates?

$$\text{Number of Stars} \times n_{\text{Earth}} = ? \times n_x = \text{ExoEarth Candidate}$$

How Many ExoEarth Candidates?

Binomial Probability Distribution

$$P_B(x, n, p) = \frac{n!}{x!(n-x)!} p^x (1-p)^{n-x}$$

n = number of tries

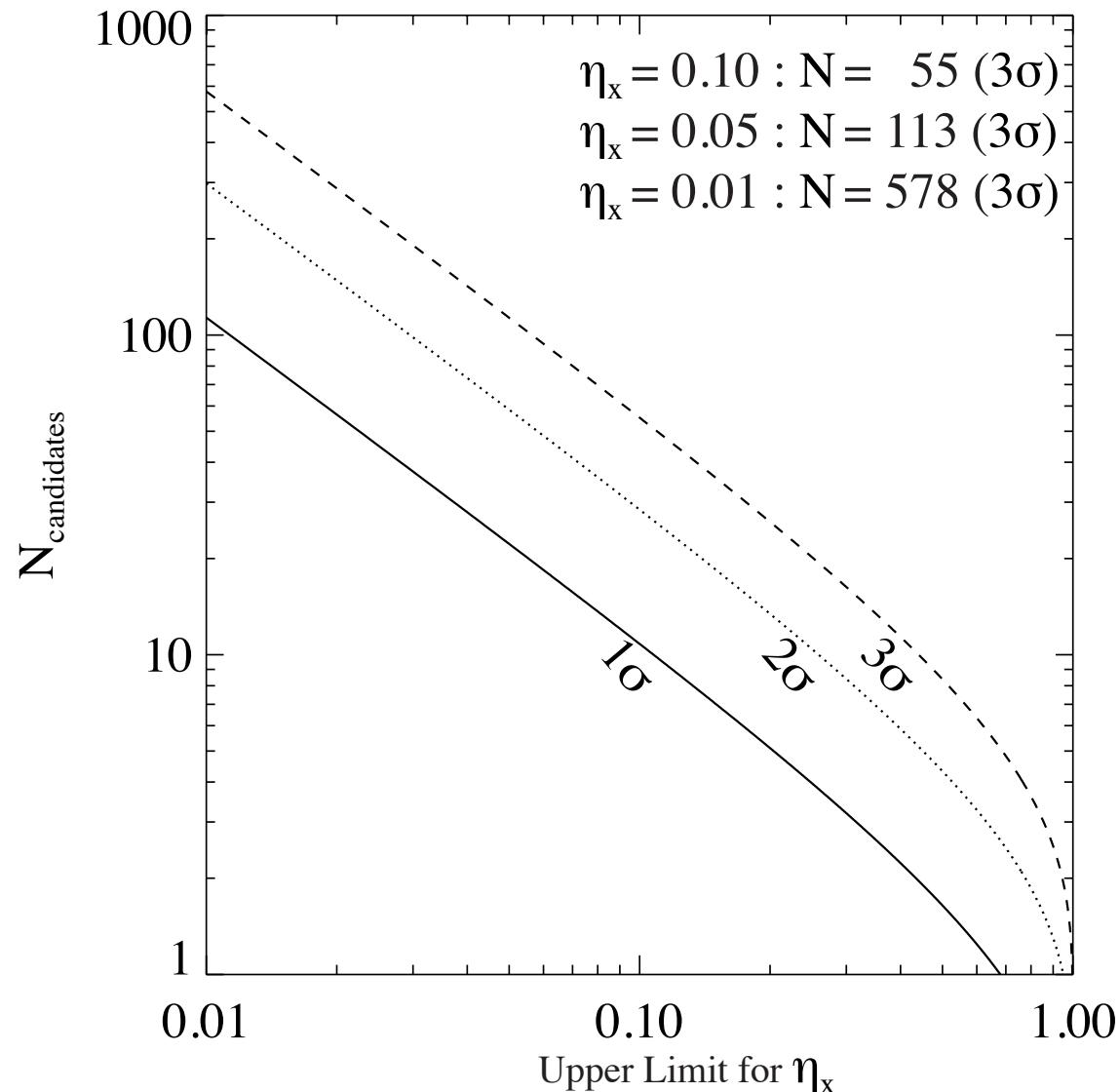
x = number of successes

p = probability of an individual success

P_B = Probability of x successes out of n tries

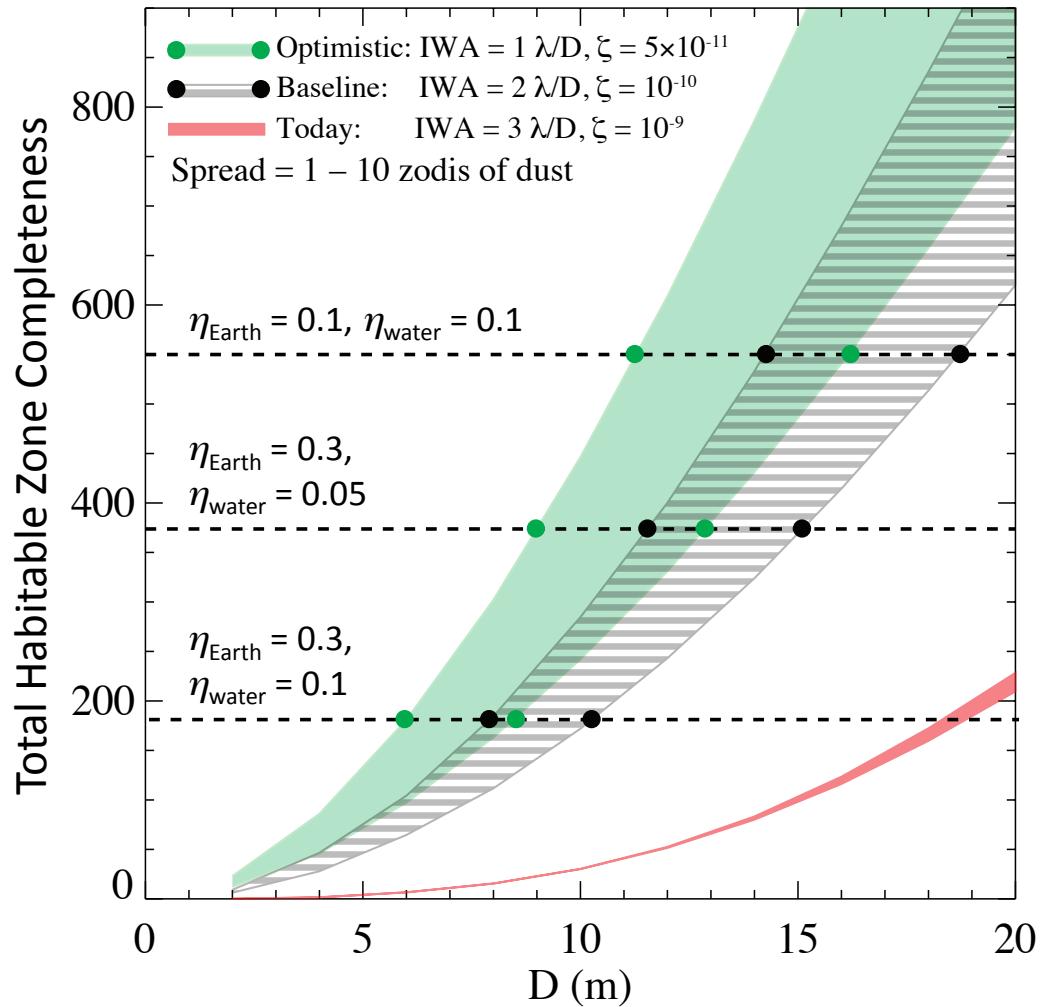
How Many ExoEarth Candidates?

Number of Candidates To Constrain η_x With a Null Result*



How Large is Large Enough?

Candidate Yield vs Aperture For Different Instrument Cases*



*Key Assumptions:

- Earth Twin (Size and Albedo)
- No revisits (will improve yield)
- Bandwidth = 20% (10% req. for H₂O)
- No spectroscopy (R = 70 for O₂)
- Exp. Time = 1 year (not incl. overh.)

Summary

- Estimated exoEarth candidate yield depends strongly on method of target prioritization & exposure time optimization
- Altruistic Yield Optimization can increase the single-visit yield of exoEarth candidates by 20-100%
- Simulated ~ 19,000 sets of mission parameters to produce conservative exoEarth yield estimates

For low η_{Earth} ...

- Single-visit exoEarth candidate yield scales roughly as $\sim D^2$
- Systematic noise floors with $\Delta \text{mag}_{\text{floor}} > 26$ do not significantly improve yield
- For any given aperture size, relative impact of exozodi on yield $\sim n^{-0.3}$